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TESTS OF THE FATIGUE STRENGTH OF CAST STEEL

A REPORT OF THE INVESTIGATION

CONDUCTED BY

THE ENGINEERING EXPERIMENT STATION

UNIVERSITY OF ILLINOIS

IN COÖPERATION WITH

THE AMERICAN STEEL FOUNDRIES

BY

HERBERT F. MOORE

BULLETIN NO. 156

ENGINEERING EXPERIMENT STATION

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ENGINEERING EXPERIMENT STATION

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HERBERT F. MOORE

RESEARCH PROFESSOR OF ENGINEERING MATERIALS
IN CHARGE, INVESTIGATION OF THE FATIGUE OF METALS

ENGINEERING EXPERIMENT STATION

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TESTS OF THE FATIGUE STRENGTH OF CAST STEEL

I. Introduction

1. *Introductory.*—The widespread and growing use of steel castings for stress-carrying members in machines and structures, and especially their use in railway rolling stock, has called attention to the lack of available data on the fatigue strength of steel castings, that is, the ability of steel castings to resist repeated stress without being fractured. Realizing the need of such data the American Steel Foundries entered into a coöperative arrangement with the Engineering Experiment Station of the University of Illinois for making a series of fatigue tests on cast steels of two different chemical compositions. The tests were carried out in the laboratories of the Investigation of the Fatigue of Metals, which has been in progress since 1919.* Although the information secured in the first series of tests is somewhat limited yet it is believed that the lack of data on the strength of cast steel justifies the publication of these results.

2. *Acknowledgment.*—Acknowledgment is made to the American Steel Foundries, whose financial support made possible the tests herein reported, and especially to Mr. J. C. Davis, Fourth Vice President, Mr. George G. Floyd, Chief Mechanical Engineer, and Mr. W. C. Hamilton, General Chief Chemist, for their helpful suggestions and their discussion of problems connected with the fatigue of steel castings.

Acknowledgment is made to Professor T. M. Jasper, Research Associate Professor of Engineering Materials and Engineer of Tests with the Investigation of the Fatigue of Metals, and to Mr. Julius Muller, Test Assistant with that investigation, who carried on much of the work of actual testing.

The tests have been a part of the work of the Engineering Experiment Station of the University of Illinois, of which Dean M. S. Ketchum is director, and of the Department of Theoretical and Applied Mechanics, of which Professor A. N. Talbot is the head.

II. Scope of Tests and Methods of Testing

3. *Scope of Tests.*—It is necessary to divide any comprehensive

*For the results of the Investigation of the Fatigue of Metals, see Bulletins 124, 136, 142, and 152 of the Engineering Experiment Station, University of Illinois.

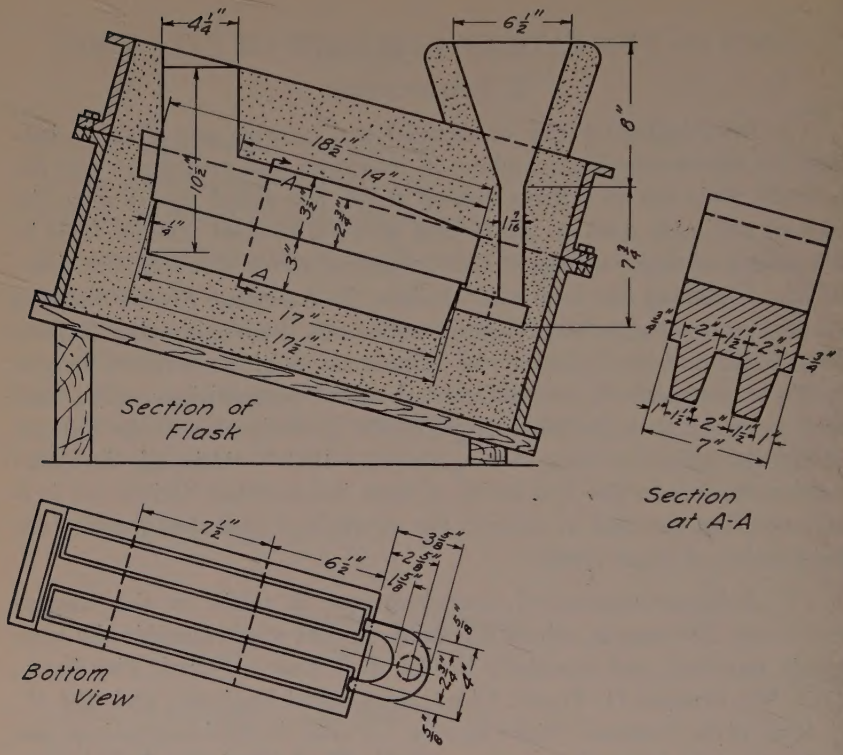


FIG. 1. MOLD FOR CASTING SLUGS OF STEEL WITH LUGS

study of the strength of steel castings into two parts: (1) the study of the strength of cast steel as a material, and (2) the study of the effective strength of this material in different parts of a casting, modified as it is by internal strains, minute cracks, and inclusions of dirt, slag, oxides, etc. The strength of cast steel as a material may be determined by means of tests of specimens cast as lugs on the under side of a fairly heavy steel casting. In the steel at this part of the casting de-

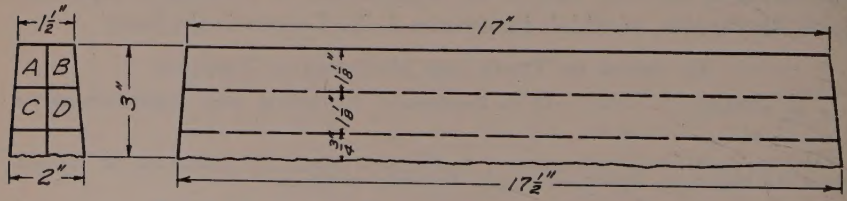


FIG. 2. SCHEME OF CUTTING SPECIMENS FROM LUGS

TABLE 1

CHEMICAL COMPOSITION OF CAST STEELS TESTED

Steel No.	Content, per cent				
	Carbon	Manganese	Silicon	Phosphorus	Sulphur
S1	0.352	1.71	0.30	0.021	0.030
S2	0.250	0.68	0.32	0.012	0.032

TABLE 2

HEAT TREATMENTS OF CAST STEELS TESTED

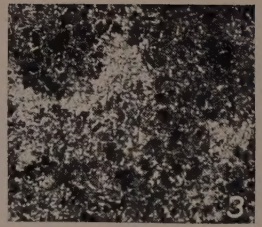
Steel No.	Heat Treatment	Detail of Heat Treatment
S1	A	Tested as received.
	B	Heat to 1650° F., hold one hour, cool in air. Reheat to 1525° F., hold one hour, cool in air.
	C	Same as treatment B, then heat to 600° F., hold one hour, cool in air.
	D	Same as treatment B, then heat to 1000° F., hold one hour, cool in air.
	E	Heat to 1525° F., hold one hour, cool in air.
	F	Same as treatment E, then heat to 600° F., hold one hour, cool in air.
	G	Same as treatment E, then heat to 1000° F., hold one hour, cool in air.
	H	Same as treatment B, then heat to 875° F., hold one hour, cool in air.
S2	A	Tested as received.
	B	Heat to 1625° F., hold one hour, cool in air.
	C	Same as treatment B, then heat to 600° F., hold one hour, cool in air.
	D	Same as treatment B, then heat to 1000° F., hold one hour, cool in air.

fects are fewest and the material in such lugs may be regarded as representative of cast steel as a material. It is evident that the study of the strength of cast steel as modified by internal strains, cracks, and inclusions in different parts of steel castings would be very complex. In this bulletin no attempt is made to discuss this second part of the problem. The tests are all tests of material from lugs cast on the under side of a fairly heavy steel casting.

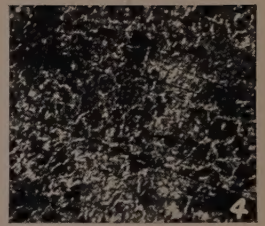
From Fig. 1 may be seen the method of casting a slug of steel with lugs in the bottom from which specimens were cut, and in Fig. 2 is shown the plan of cutting four test specimens from a lug. All

As received

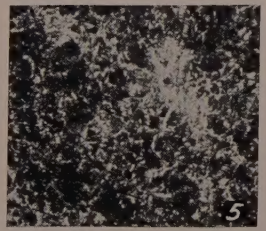
Heated to 1425° F.,
held 1 hour,
cooled in air.



Heated to 1500° F.,
held 1 hour,
cooled in air.

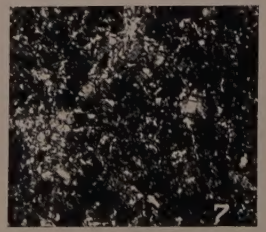


Heated to 1500° F.,
held 2 hours,
cooled in air.

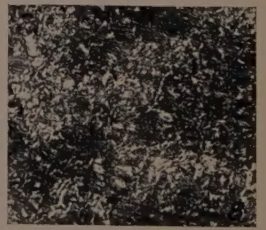


Heated to 1500° F.,
held 3 hours,
cooled in air.

Heated to 1625° F.,
held 1 hour,
cooled in air.



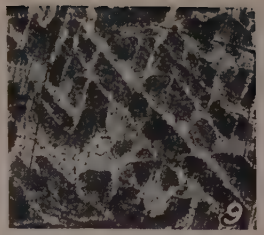
Heated to 1625° F.,
held 2 hours,
cooled in air.



Heated to 1625° F.,
held 3 hours,
cooled in air.

Micrographs of Steel No. 81, 75 diameters.

FIG. 3. MICROGRAPHS, FIRST SERIES OF HEAT TREATMENTS



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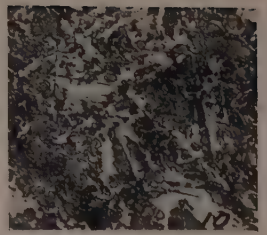
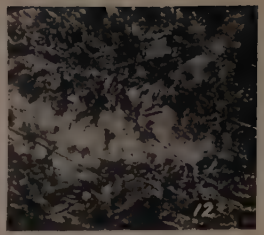
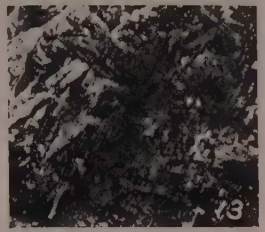


Heated to 1425° F.,
held 1 hour,
cooled in air.

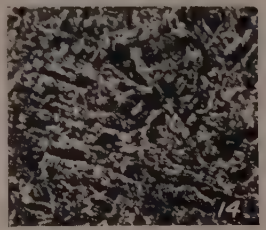
Heated to 1425° F.,
held 3 hours,
cooled in air.



Heated to 1500° F.,
held 1 hour,
cooled in air.

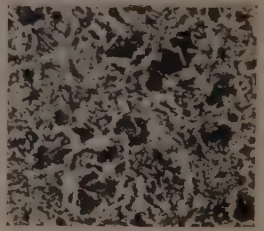


Heated to 1500° F.,
held 2 hours,
cooled in air.



Heated to 1500° F.,
held 3 hours,
cooled in air.

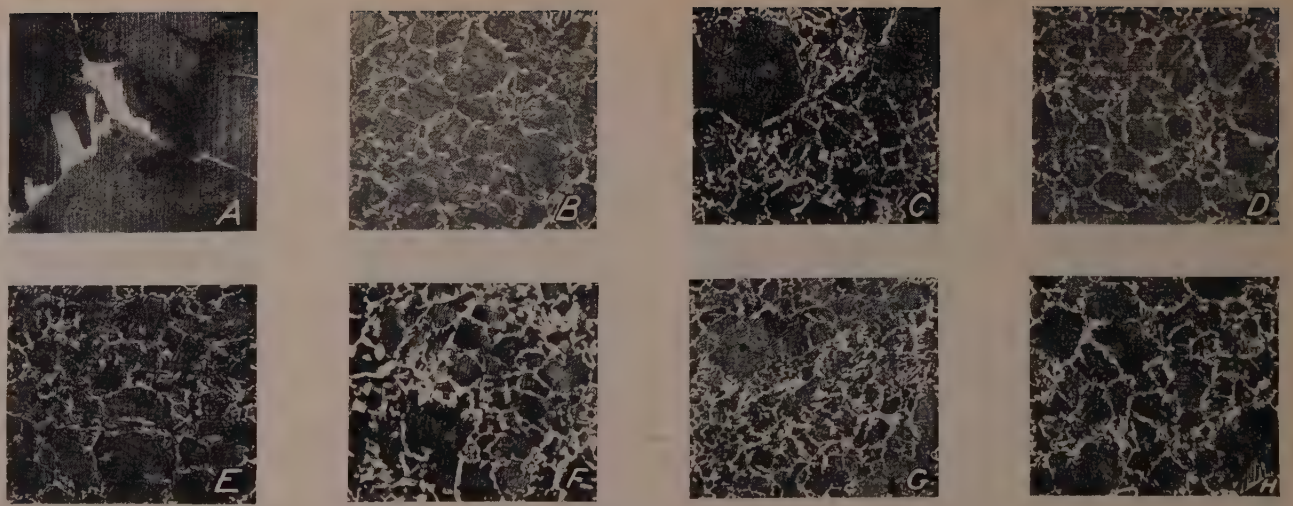
Heated to 1625° F.,
held 1 hour,
cooled in air.



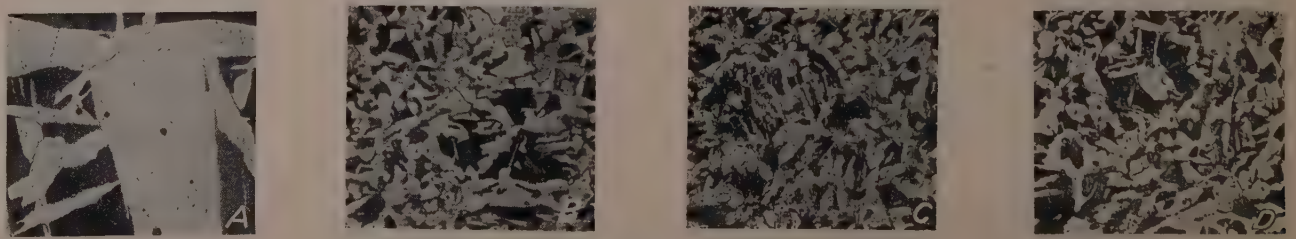
Heated to 1625° F.,
held 3 hours,
cooled in air.

Micrographs of Steel No. 82, 75 diameters.

FIG. 3. (Concluded). MICROGRAPHS, FIRST SERIES OF HEAT TREATMENTS



Steel No. 81, 100 diameters



Steel No. 82, 100 diameters

Letters refer to heat treatments. For details of heat treatments see Table 2.

FIG. 4. MICROGRAPHS, SECOND SERIES OF HEAT TREATMENTS

Table 3

Test Data of Rotating-Beam Fatigue Tests of Cast Steel

Speed of testing machines, 1500 r.p.m.

Specimen No.	Stress in lb. per sq. in.	Cycles for Failure	Treatment
Cast Steel No. 81			
81 N 4B	50 200	82 100	A
81 E 0B	43 000	398 000	"
81 L 4A	40 000	400 600	"
81 E 0C	37 000	1 074 100	"
81 L 4D	34 000	2 343 200	"
81 H 4D	32 000	2 273 900	"
81 C 0B	31 500	102 778 400*	"
81 N 4B	30 100	110 735 500*	"
81 N 4A	63 500	84 200	B
81 V 4D	54 000	247 900	"
81 C 0A	50 000	1 165 000	"
81 V 4A	47 000	96 638 900*	"
81 K 0A	45 400	901 400	"
81 V 4B	43 000	96 544 400*	"
81 N 4A	40 000	86 622 800*	"
81 V 0C	55 000	138 800	C
81 AA 0A	50 000	763 800	"
81 W 0A	48 100	598 400	"
81 J 4A	46 100	20 574 300	"
81 F 4A	45 000	1 592 900	"
81 Q 0A	44 000	75 180 600*	"
81 H 4C	62 000	85 500	D
81 N 4C	50 000	247 200	"
81 H 4A	47 000	730 800	"
81 C 0C	45 000	325 300	"
81 L AB	44 000	104 309 300*	"
81 I 0A	43 000	101 583 400*	"
81 C 0D	40 000	48 138 600*	"
81 H 4C	39 300	37 055 500*	"
81 J 4D	50 500	384 900	E
81 J 4C	49 300	644 600	"
81 EE 0C	48 500	22 911 000	"
81 EE 0D	47 900	94 611 700*	"
81 Q 0D	46 500	55 113 400*	"
81 I 4D	44 000	10 710 700*	"
81 G 0B	50 000	538 200	F
81 O 0B	47 000	914 100	"
81 J 4B	45 000	676 900	"
81 W 0B	45 000	790 400	"
81 AA 0B	43 000	82 284 600*	"
81 V 0A	42 200	83 506 800*	"
81 DD 4B	54 000	384 400	G
81 V 0D	53 000	384 600	"
81 EE 0A	50 000	95 894 600*	"
81 G 0B	46 000	10 196 700	"
81 K 0B	45 000	11 251 300	"
81 F 4B	43 600	5 430 300	"
81	42 100	53 192 100*	"
81 OO D	46 400	402 100	H
81 F 4C	46 000	962 000	"
81 O 0C	45 300	1 573 000	"
81 G 0G	45 000	378 000	"
81 W 0C	42 900	23 783 000*	"
81 G 0D	40 000	65 584 000*	"

*Specimen did not fracture.

TABLE 3—*Concluded*

Specimen No.	Stress in lb. per sq. in.	Cycles for Failure	Treatment
Cast Steel No. 82			
82 F 44	45 000	13 000	A
82 X 4C	37 000	337 100	"
82 W0D	33 000	1 056 300	"
82 Y0B	30 100	1 593 200	"
82 O0C	29 000	2 817 000	"
82 D4B	27 400	93 187 700*	"
82 V4R	27 300	55 806 500	"
82 F44	25 000	9 218 000*	"
82 FAD	41 500	142 600	B
82 N4A	38 000	5 101 500	"
82 O0R	36 100	12 595 700	"
82 K0A	35 000	81 571 000*	"
82 S0C	46 000	41 400	C
82 F 4B	39 900	645 800	"
82 N 4C	35 000	966 800	"
82 D 4D	32 000	2 606 500	"
82 O0D	31 100	99 011 200*	"
82 V 4D	30 000	99 191 800*	"
82 O0 A	48 000	152 600	D
82 X 0D	42 000	479 500	"
82 X 4A	37 100	1 599 200	"
82 D 44	34 000	952 900	"
82 P 4A	33 100	1 521 900	"
82 D 4C	32 900	68 877 500*	"
82 O0A	29 500	34 315 000*	"

*Specimen did not fracture

castings were made in the Granite City (Illinois) plant of the American Steel Foundries, and the lugs, cut off from the castings by means of an oxyacetylene torch, were shipped to the Materials Testing Laboratory of the University of Illinois. Specimens were machined from the lugs in such a manner that no material in any test specimen was located within $\frac{7}{8}$ of an inch of the torch-cut in the lug from which the specimen was cut.

4. *Chemical Composition and Heat Treatment of Steels.*—Two kinds of steel were furnished for the tests which have been given the identifying laboratory numbers 81 and 82, respectively. Steel No. 81 is a steel with a high manganese content, and has been given the trade name "Hylastic" by the American Steel Foundries. The chemical composition of Steel No. 82 is fairly representative of ordinary steel castings. The chemical composition of both is given in Table 1.

Two metallographic studies were made of the effect of heat treatment on the crystalline structure of the steel. No heat treatments were used which involved water quenching or oil quenching. The

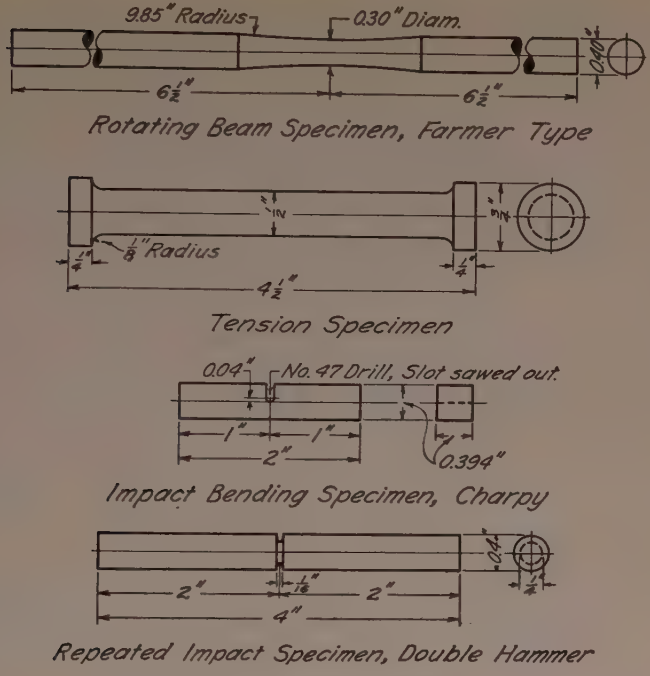


FIG. 5. TEST SPECIMENS

micrographs in Fig. 3 show the results of the first series of heat treatments. The maximum temperature and the time of "soaking" at maximum temperature were the variables studied. The micrographs show that it is possible to improve markedly the coarse-grained, somewhat dendritic, structure of the steel as cast, and to make it fairly fine grained. It is quite probable that a more extended study would disclose other heat treatments which would give to the steel a still finer-grained structure. In this series the pieces heat treated were about 1 inch by ⅞ inch in cross-section.

The micrographs in Fig. 4 show the results of the second series of heat treatments. They show the crystalline structures corresponding to the heat treatments for the test specimens used in determining the strength of the steel. The letters in Table 2 denoting heat treatment correspond to the letters denoting micrographs in Fig. 4. The details of the various heat treatments given to specimens are given in Table 2. These heat treatments were suggested by the American Steel Foun-

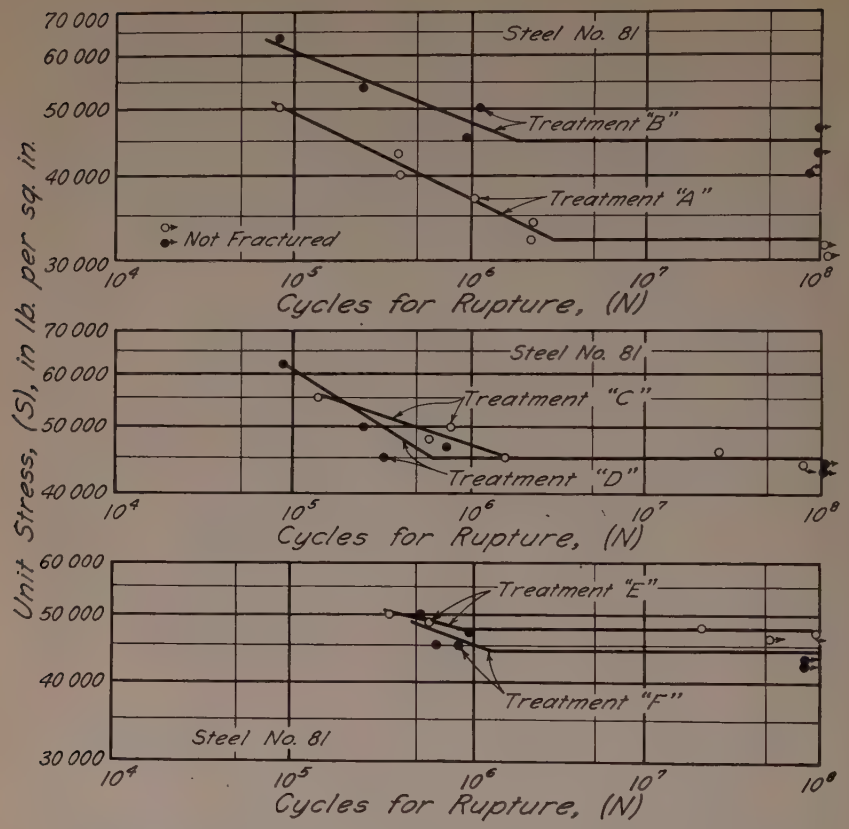


Fig. 6. *S-N* Diagrams for Fatigue Tests of Steel No. 81, Heat Treatments A, B, C, D, E, and F

dries. The heat treatments listed in Table 2 were given to pieces of steel about ⅞ inch square, cut from the lugs shown in Figs. 1 and 2. From these heat treated pieces test specimens were machined. All heat treatments for both series of tests were made in a Hoskins electric resistance furnace.

5. *Test Specimens and Methods of Testing.*—The pieces of steel cut from the lugs of the castings were approximately 17 inches long by ⅞ inch square. After heat treatment (if any) each bar was cut into two parts whose approximate lengths were 13 inches and 4 inches, respectively.

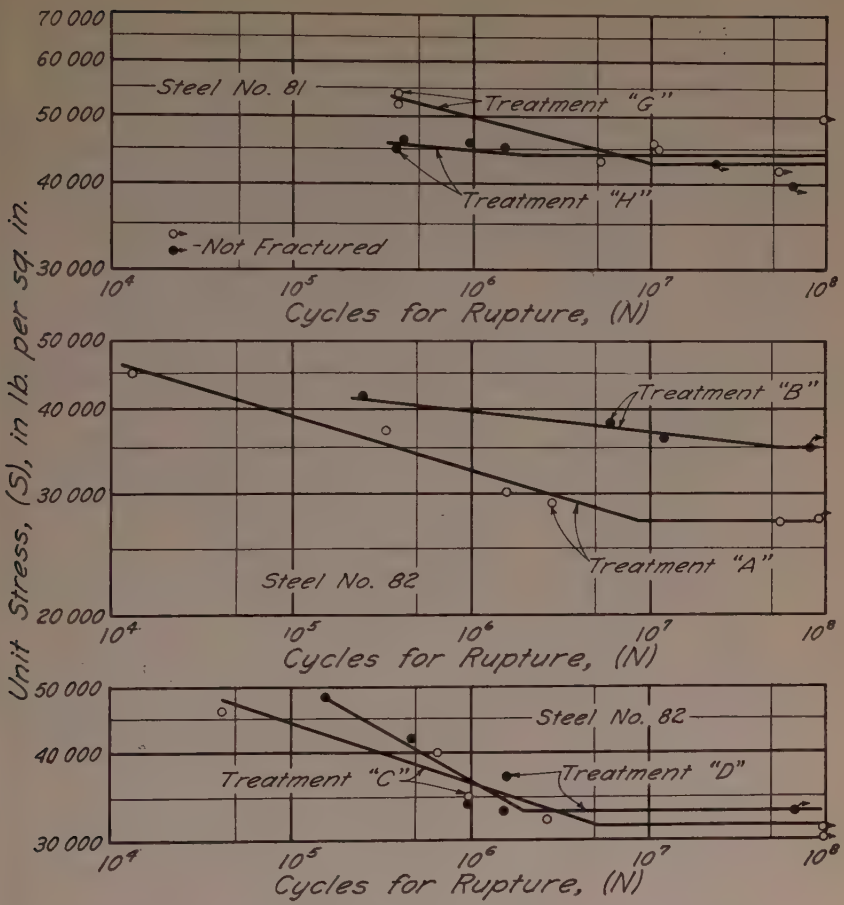


FIG. 7. *S-N* DIAGRAMS FOR FATIGUE TESTS OF STEEL NO. 81, HEAT TREATMENTS G AND H, AND OF STEEL NO. 82, HEAT TREATMENTS A, B, C, AND D

The various test specimens used are shown in Fig. 5. The Charpy test specimens were machined from the 4-inch pieces, the rotating-beam fatigue specimens and the tension specimens from the 13-inch pieces. The repeated-impact specimens were machined from the ends of the broken rotating-beam specimens. After machining, all specimens were allowed to rest at room temperature for a period of two weeks before being tested.

Table 4

Results of Tension Tests, Charpy Tests, Repeated-Impact Tests, Hardness Tests, and Fatigue Tests of Cast Steel

Steel No.	Heat Treatment	Static Tension Tests					Charpy (notched bar) Test	Repeated Impact Test No. of Double Blows	Brinell Number	Fatigue Tests	
		Proportional Elastic Limit	Yield Point	Ultimate Tensile Strength	Elongation in 2 in.	Reduction of Area				Endurance Limit (Rotating Beam) lb. per sq. in.	Endurance Ratio*
		lb. per sq. in.			per cent		ft. lb.				
81	A	39 000	.....	80 800	2.1	4	2.8	30	179	32 000	0.40
	B	42 400	.....	108 900	14.4	26	20.2	491	197	45 000	0.41
	C	46 800	.....	104 200	25.1	56	28.4	407	196	45 000	0.43
	D	59 600	.....	103 600	22.5	48	30.7	511	188	45 000	0.43
	E	47 500	.....	107 600	13.7	23	22.1	475	201	48 000	0.45
	F	49 000	.....	103 600	25.0	53	28.7	487	192	44 000	0.42
	G	58 600	.....	102 600	26.8	56	32.3	489	196	43 000	0.42
	H	56 200	.....	104 300	23.4	53	28.8	569	199	44 000	0.42
82	A	23 600	26 700	67 200	22.0	33	20.1	209	119	27 000	0.40
	B	42 800	43 600	76 600	30.5	51	32.6	279	136	35 000	0.46
	C	43 000	43 100	77 100	31.5	52	32.0	254	136	31 000	0.40
	D	41 300	42 700	76 100	31.7	56	34.0	291	133	33 000	0.43

*The endurance ratio is the ratio of endurance limit to ultimate tensile strength.

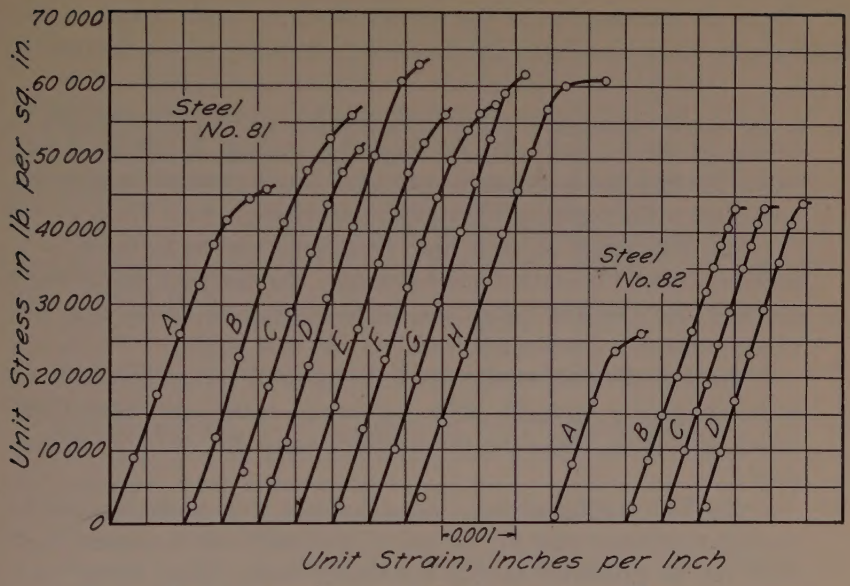


FIG. 8. STRESS-STRAIN DIAGRAMS FOR STEELS TESTED

The tension tests were made on a 100 000-lb. screw-power testing machine, the hardness tests on an Alpha Brinell machine, the Charpy tests on an American built Charpy machine, the repeated-stress tests on a Sondericker (or Farmer) type rotating-beam machine, and the repeated-impact tests on a double-hammer machine built in the shops of the Materials Testing Laboratory of the University of Illinois. The machines, the technique of testing, and the methods of reducing test data are the same as those described in some detail in Bulletin No. 124 of the Engineering Experiment Station of the University of Illinois.

III. RESULTS AND CONCLUSIONS

6. *Test Data and Results.*—The data of the fatigue tests are given in Table 3. These data are also shown graphically in the *S-N* diagrams of Figs. 6 and 7. Typical stress-strain diagrams for the tension tests are shown in Fig. 8.

Summarized results of the static tension tests, the Brinell tests, the Charpy tests, the repeated-impact tests, and the repeated-stress tests are given in Table 4.

From an examination of the results given in Table 4 and of the micrographs shown in Fig. 4 the following summary of conclusions is given:

(1) As cast, the steels tested showed a coarse-grained crystalline structure; steel No. 82 showed a marked dendritic structure. By suitable heat treatment it was found possible to give the cast steel a finer-grained crystalline structure.

(2) The result of such heat treatment was to increase to a marked degree the static tensile strength, the ductility, the Brinell number, the Charpy value, the repeated-impact value, and the fatigue strength (endurance limit) of the cast steels.

(3) For the cast steels tested the ratio of endurance limit to ultimate tensile strength (the endurance ratio) averages 0.42, which is slightly less than the average value for ordinary rolled steel.*

(4) The results of these tests indicate that under favorable casting conditions and by the use of suitable heat treatment cast steel can be produced having a strength under either static load or repeated load, only slightly less than the strength of rolled steel of similar chemical composition.

*This result in a general way checks the results of fatigue tests of cast steel made by Lessells at the Westinghouse Electric and Manufacturing Co. and reported in "Applied Elasticity" by Timoshenko and Lessells, p. 473-476.

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